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# GIS-based assessment of combined CSP electric power and seawater desalination plant for Duqum—Oman

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ABSTRACT

This paper investigates the potential of implementing combined electric power and seawater desalination plant using concentrated solar power technologies for Wilayat Duqum in Oman. Duqum is going through a considerable urban, touristic and industrial expansion and development. GIS solar radiation tools are used to select the most appropriate site for the plant location. There are basically two different options to combine concentrated solar electric power with seawater desalination. The first option is to combine a CSP plant with a thermal desalination unit, exploiting the exhaust heat of the steam cycle to drive a thermal desalination unit. The second option is to exploit only the electricity output of the CSP plant with a reverse osmosis desalination unit. The paper deals with both options and shows where each of the concepts has advantages considering local conditions: the quality of the input water, the demand of freshwater and/or potable water, social and economic aspects, the environment and others.



**Contents**



## 1. Introduction

The general perception of "solar seawater desalination" is often restricted to only small-scale technologies for decentralized water supply in remote and rural areas, but do not address the increasing water deficits of the quickly growing urban centers of demand. Conventional large-scale desalination technologies are usually perceived as expensive, energy consuming and limited to oil-rich countries like those of the GCC, especially. The environmental

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impacts of large-scale water desalination are increasingly considered as critical because of their airborne emissions of pollutants from fossil–fuel energy consumption and to the discharge of brine and chemical additives to the sea. For those reasons, most contemporary strategies against a "Global Water Crisis" consider seawater desalination only as a marginal element of supply. The focus of most recommendations lies on more efficient use of water, better accountability, re-use of waste water, enhanced distribution and advanced irrigation systems. To this adds the recommendation to reduce agriculture and rather import food from other places. On the other hand, most sources that do recommend seawater desalination as part of a solution to the water crisis usually propose nuclear fission and fusion as indispensable option.

None of the presently discussed strategies include concentrating solar power (CSP) for seawater desalination within their portfolio of possible alternatives. However, quickly growing population and water demand and quickly depleting groundwater resources in the arid regions such as Oman require solutions that are affordable, secure and compatible with the environment—in one word: sustainable. Such solutions must also be able to cope with the magnitude of the demand and must be based on available or at least demonstrated technology, as strategies bound to uncertain technical breakthroughs – if not achieved in time – would seriously endanger the whole country and the region.

From all available renewable energy sources, solar energy is the one that correlates best with the demand for water, because it is obviously the main cause of water scarcity. The resource-potential of concentrating solar power dwarfs global energy demand by several hundred times. The environmental impact of its use has been found to be acceptable, as it is based on abundant, recyclable materials like steel, concrete and glass for the concentrating solar thermal collectors. Its cost is today equivalent to about 50 US$/barrel of fuel oil (8.8 US$/GJ), and coming down by 10–15% each time the world wide installed capacity doubles [1]. In the medium-term by 2020, a cost equivalent to about 20 US$/barrel (3.5 US$/GJ) is expected to be achieved. In the long-term, it will become one of the cheapest sources of energy, at a level as low as 15 US$/barrel of oil (2.5 US$/GJ). It can deliver energy "around-the-clock" for the continuous operation of desalination plants, and is certainly the "natural" resource for seawater desalination.

The present paper analyses the potential of concentrating solar thermal power technology for large-scale electric power seawater desalination plant for Wilayat Duqum in Oman. It provides a comparison on technology options, water demand, reserves and deficits and derives the short-, medium- and long-term markets for solar powered desalination. The paper gives a first information base for a political framework that is required for the initiation and realization of such a scheme. It quantifies the available solar energy resources for Wilayat Duqum and the expected cost of solar energy and desalted water, a long-term scenario of integration into the water sector, and quantifies the environmental and socio-economic impacts of a broad dissemination of this concept.

## 2. Location and topography of Wilayat Duqum

The Sultanate of Oman occupies the South-Eastern corner of the Arabian Peninsula and is located between latitudes 16°40′ and 26°20′ north and longitudes 51°50′ and 59°40′ east (Fig. 1). It has a coastal line extending almost 3165 km, from the Strait of Hormuz in the North to the borders of the Republic of Yemen, overlooking three seas; the Arabian Gulf, Gulf of Oman and the Arabian Sea [2].

The Sultanate of Oman borders Kingdom of Saudi Arabia and the United Arab Emirates in the West; the Republic of Yemen in the South; the Strait of Hormuz in the North and the Arabian Sea in the East. Wilayat Duqum is located in the south-eastern corner of Al-Wusta, neighboring the Wilayat of Mahut in the north, the Wilayat of Jazur in the south, the Wilayat of Haima in the west and in the east the Arabian Sea, shown in Fig. 1. There are presently more than 4276 inhabitants living in about 23 villages [3].

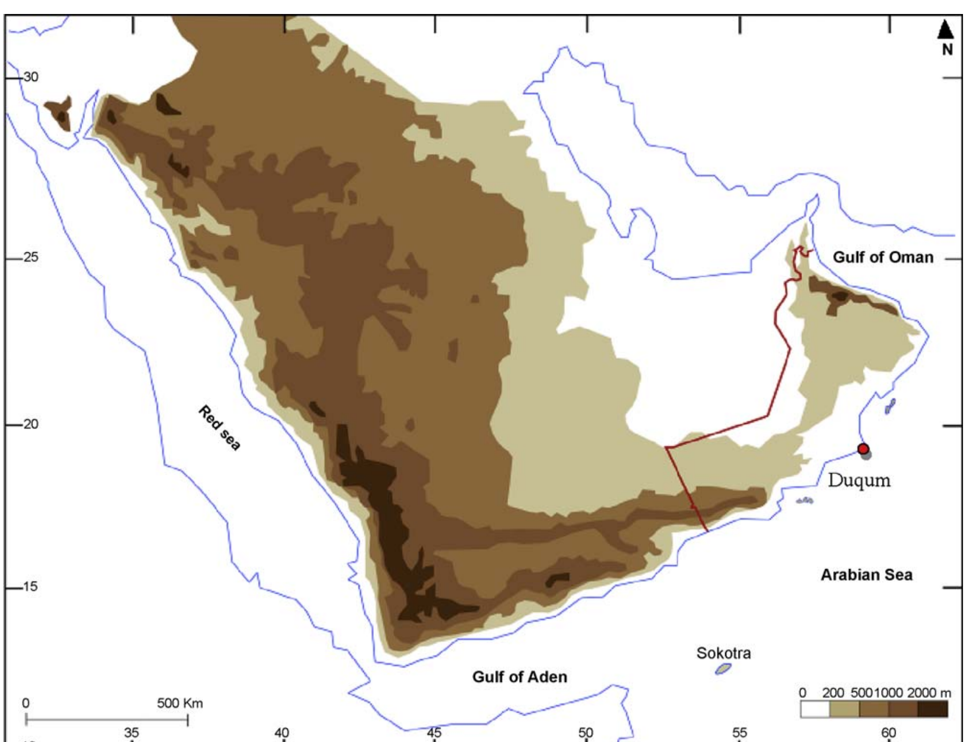


**Fig. 1.** Location of Oman in the Arabian Peninsula.

## 3. Expansion plan of Wilayat Duqum

Duqum is hardly a destination for the average tourist or leisure-traveler, leave alone industrialists. But come 2010, Oman's most comprehensively planned town will blip on the global industrial radar like no other Omani city [4]. A comprehensive master plan has been prepared for Duqum by the Supreme Committee for Town Planning, Sultanate of Oman. The master plan has designated areas for airport, petroleum refinery and oil storage facilities along with downstream industries, a fishing harbor with fishery related industries, free trade zones, general industries and tourism projects. It has planned a complete residential town with a Town Centre and all modern amenities [4]. The population is expected to grow up to 100,000 inhabitants by 2020.

What is considered now as a sleepy, fishing town is soon expected to experience a fast-developing industrial hub. If all goes according to the master plan, Duqum will be a force to consider within the entire Gulf region in the near future. Thanks to its proximity to the busy regional sea-lanes traversing Oman's coastal waters, Duqum – about 600 km from Muscat – is being conceived as a main maritime gateway that will serve an ambitious industrial and commercial hub. Apart from the strategic location of Duqum, the friendly climate of the area adds to its advantages.

The purpose behind developing Duqum is to export Gulf's crude oil from an Omani port. Outline of the ambitious plan is to export crude oil, which is produced in the Gulf region and transported through pipeline to Duqum. Positioned as it is on the Gulf of Oman, with the Strait of Hormuz and the Arabian Sea at its north-eastern end, and with its long coastline running south along the Arabian Sea, the government believes Duqum is strategically the most preferred location for this port.

## 4. Oman's water resources

Oman relies mainly on groundwater which represents 78% of the total supply out of 1430 $Mm^3$/year. Surface water resources are very scarce and represent only 6% of the total supply (see Fig. 2).

Seventy-eight percent of the total water supply is used in the agricultural sector. Seawater desalination is becoming the major source of urban water supply. In fact, during the period 1999–2008 desalination has grown from a 3% of total water supply to 13%. Wastewater re-use is also growing and represents currently 3% of total supply. Most of the treated wastewater is being used for roads landscaping and public parks irrigation, even though some types of industry started using tertiary treated wastewater because it costs only 20% of the desalinated water price.

Oman has witnessed a remarkable increase in the production of non-conventional water during the past 10 years: desalination water and treated wastewater were only 3% and 1%, respectively.

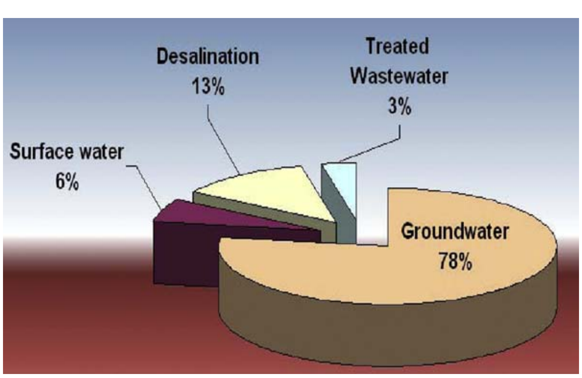


**Fig. 2.** Conventional and non-conventional water use.

Urban water demand is booming and desalination is the only reliable source capable of supplying the required quantities in the near future. It is expected that by 2013 some 221 $Mm^3$/year will be required to satisfy the demand in the four major urban areas of Muscat, Sohar, Sharqiya and Dhofar. These figures do not take into account the needs for Duqum area, which consists of the creation of a new tourism and industrial city with 100,000 inhabitants. Seawater desalination represents 93.4% of total desalination water. The remaining part is brackish water desalination from wells, in the interior regions and based on small-scale plants. Gas is the energy used for desalination in the major plants. The volume of natural gas used in 2006 was estimated at 4454 million $Sm^3$. This figure is expected to reach at least 7174 million $Sm^3$. In GJ, the energy requirement is expected to rise from 177 million in 2006 to a minimum of 262 million GJ by 2013 [5]. The private sector has built, owns and is operating the latest dual electricity seawater desalination plant with an initial capacity to produce 91,000 $m^3$/day using multi-stage flash technology and 427 MW. The second phase of the project is expected to be operational by end of 2009. Its production capacity will be 120,000 $m^3$/day and it uses reverse osmosis technology. Thus, it is possible to confidently conclude that the lowest cost of desalination in Oman is by using reverse osmosis technology.

## 5. Different configurations for CSP desalination

Referring to [1], there are three different systems that can be considered for CSP water desalination (see Fig. 3): small-scale decentralized desalination plants directly powered by concentrating solar thermal collectors, concentrating solar power stations providing electricity for reverse osmosis membrane desalination (CSP/RO), and combined generation of electricity and heat for thermal multi-effect desalination systems (CSP/MED). It was proved that multi-stage flash (MSF) desalination, although at present providing the core of desalted water in the Middle-East, has not been considered as viable future option for solar powered desalination, due to the high energy consumption of the MSF process.

In [1], reference systems for CSP/RO and for CSP/MED were defined with 24,000 $m^3$/day of desalting capacity and 21 MW net electricity to consumers. An annual hourly time-step simulation for both plant types was made in order to compare their technical and economic performance under specific environmental conditions.

Both systems were found to have the medium-term potential to achieve base-load operation with less than 5% of fuel consumption of conventional plants, at a cost of water well below 0.4 US$/$m^3$. Today, such integrated plants have been found to be already

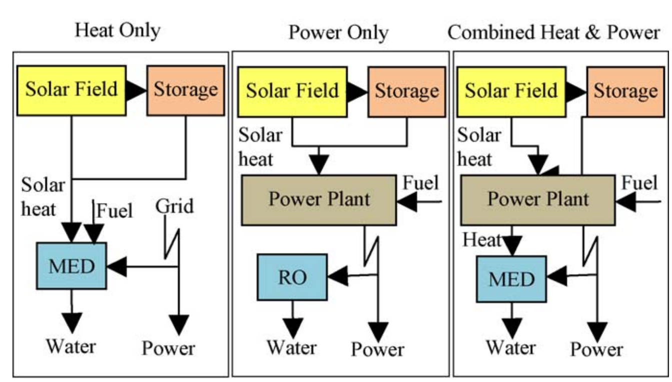


**Fig. 3.** Different configurations for desalination by concentrated solar power. Left: concentrating solar collector field with thermal energy storage directly producing heat for thermal multi-effect desalination. Center: power generation for reverse osmosis (CSP/RO). Right: combined generation of electricity and heat for multi-effect desalination (CSP/MED).

**Table 1**
Comparison between CSP/MED and CSP/RO plant technologies.

| System | CSP/MED | CSP/RO |
|---|---|---|
| Site selection | Limited to coastal areas | CSP may be anywhere, RO must be at the coast, while the public grid can be used for interconnection |
| Flexibility | Interdependent operation | Independent operation possible if plants interconnected through the public grid |
| Optimal irradiance | Defined by coastal site | CSP can be placed at site with higher irradiance, but certain amount of power is then lost by transmission to RO plant, and dry cooling leads to lower efficiency |
| Storage options | Molten salt, concrete, low temperature hot water storage possible, PCM | Molten salt, concrete, phase change materials (PCM) |
| Water quality | Independent of raw water quality, very high quality of product water | May be favorable for brackish raw water and if low product water quality is allowed |
| Other uses | Industrial co-generation of process heat, district cooling, integrated systems for power, cooling, desalination for tourism and rural development | Power only |

competitive in some niche markets, like e.g. onsite generation of power and water for very large consumers like hotel resorts or industry.

A comparison between the CSP/MED and CSP/RO plants is summarized in Table 1 [1]. It was proven that the direct coupling of CSP with MED has certain advantages [1]: first of all, the primary energy consumption is reduced, and with that, the environmental impact of the plant. It was also shown that this type of integrated plants is very attractive for large consumers like hotel resorts or industrial parks, because on-site operation of such plants can be highly competitive with power and water purchase prices from external sources.

Due to its better technical performance, CSP/MED requires a 10% smaller collector field than CSP/RO. The substitution of the cooling system by the MED plant leads to a 10% lower investment for the power block than in the case of CSP/RO. On the other hand, the investment needed for the MED plant is about 50% higher than that of an equivalent RO plant. All in all, the total investment of CSP/MED is about 10% higher than that of CSP/RO [1].

The economic performance of the combined generation of electricity and desalted water was compared by fixing the sales price for electricity at 0.09 US$/kWh which would be the production cost of a gas-fired combined cycle power station and subtracting the resulting annual electricity revenue from the total annual expenditure. The remaining annual cost was charged to the annual desalted water production, yielding the average cost per cubic meter of desalted water, which resulted to be in the range of 2.00–2.40 US$/m$^3$.

In all cases the CSP/MED configuration shows a slightly lower cost of water than CSP/RO. Due to the better technical performance of the CSP/MED system, fuel consumption is about 10% lower than that of CSP/RO. To this adds the necessary replacement of RO membranes every five years. These cost items make up for a slightly better economic performance of the CSP/MED system, in spite of its higher initial investment cost. Again, this result is contrary to the commonly presumed statement that RO is cheaper than MED. Although this may be true in terms of investment, in the case of a combined CSP/desalination plant, the overall result is opposite, although the difference in cost among both systems is not very large. Therefore, we believe that only in-depth, project-wise analysis of technical and economical performance can lead to a well-founded decision for the one or the other technical configuration of the most appropriate CSP-desalination system, and competition will define the shares of the different existing options in the future desalination market.

However, in general, it can be considered that there is no clear preference for one or the other plant type or combination, and that there will be considerable future markets for both CSP/MED and CSP/RO plants.

## 6. Site selection

As mentioned above, the site selection depends on the CSP-desalination technology, solar radiation, land slope, proximity of seawater, and availability of sufficient land area. To combine all these criteria and select an appropriate location for the CSP-desalination plant, the Geographical Information System (GIS) tool ArcGIS is used with high resolution (40 m $\times$ 40 m cells) Digital Elevation Model (DEM) of the Duqum region. Duqum expansion master plan is also investigated and integrated with the DEM. For efficient implementation of CSP, it is known that it is preferable to select lands with slopes less than 1%. ArcMap is used to first classify the land according to slopes. Then, land areas with slopes bigger than 1% are removed. Since CSP plants require large surfaces, land areas with surfaces less than 2 km$^2$ are also removed. Finally, ArcGIS solar radiation calculation tool is used to calculate the solar radiation on remaining filtered areas.

With landscape scales, topography is a key factor that determines the spatial variability of radiation. Variation in elevation, orientation (slope and aspect), and shadows cast by topographic features all affect the amount of radiation received at different locations [6]. This spatial variability also changes with time of day and time of year. The solar radiation analysis tools, in the ArcGIS Spatial Analyst extension, enable to map and analyze the effects of the sun over a geographic area for specific time periods. It accounts for atmospheric effects, site latitude and elevation, steepness (slope) and compass direction (aspect), daily and seasonal shifts of the sun angle, and effects of shadows cast by surrounding topography [6]. Incoming solar radiation originates from the sun, is modified as it travels through the atmosphere, is further modified by topography and surface features, and is intercepted at the earth's surface as direct, diffuse, and reflected components. The sum of the direct, diffuse, and reflected radiation forms the global solar radiation. In general, direct radiation is the principal component of total radiation, and diffuse radiation is the second largest component.

The solar radiation tools in ArcGIS Spatial Analyst do not include reflected radiation in the calculation of total radiation [6]. Therefore, the total radiation is calculated as the sum of the direct and diffuse radiations. This involves six steps as illustrated by the flowchart in Fig. 4.

Fig. 5 shows the ArcGIS slopes, surfaces, and solar radiation calculation results obtained for Duqum. Note that only the most interesting portion of Wilayat Duqum is zoomed in Fig. 5.

Based on the development plan of Duqum, and the topologies of the land areas in the region, it is suggested that, for the CSP technologies requiring large amount of water for desalination and mirrors' washing, the selected area is a flat land (slope $<$1%) located proximity to the sea ($\sim$2 km) inside a total projected industrial area

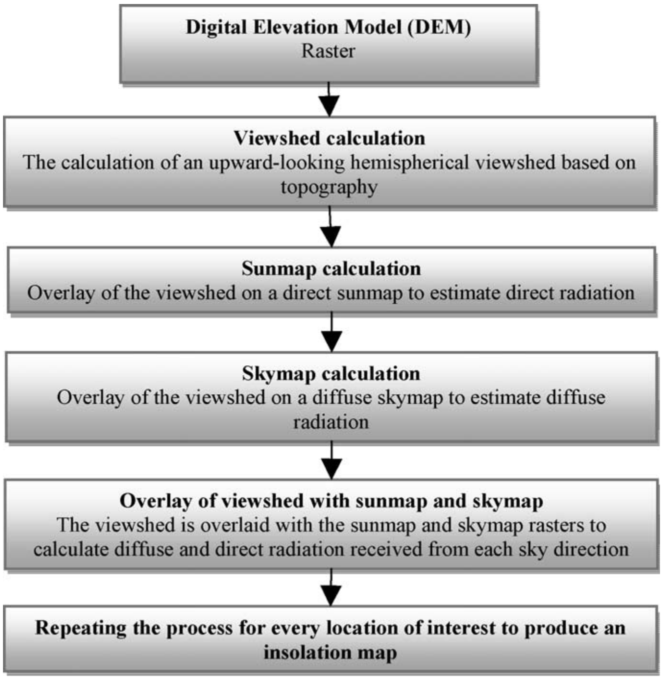


**Fig. 4.** Steps followed to calculate solar radiation on a DEM using ArcMap.

of around 50 $km^2$, hence, allowing easy future expansion of the plants. It was proposed to start with a 100 MW power plant which is expected to consume around 2–3 $km^2$ of flat land for the Parabolic Trough CSP technology electric power and desalination plant. The total calculated potential of yearly electricity generation would be about 1.6 TWh. If half of the selected land (0.5 km $\times$ 50 km) is reserved for future expansion of the plant, the total future capacity can attain 1 GW of electric power. The selected area can also accommodate in the future different types of CSP technologies (i.e. Fresnel technology) as they mature with time.

## 7. Benefits of large-scale CSP-desalination systems

Duqum consists of the creation of a new tourism and industrial city with 100,000 inhabitants. Assuming a consumption of 2.34 $m^3$/family/day, the domestic demand will reach 60,000 $m^3$/day. For the industrial demand we assume 14,000 $m^3$/day, as in Sohar, a city with similar industrial facilities, mainly a port and refinery. This brings the total daily demand in Duqum to around 75,000 $m^3$ or 28 $Mm^3$/year. The investment cost of a RO seawater desalination plant is around US$ 800/$m^3$ day capacity. This implies that for a natural gas fuel based desalination plant in Duqum we should expect an investment cost around US$ 60 million. The full cost of seawater desalination using RO is around US$ 0.5/$m^3$ [7].

There are several good reasons for the implementation of large-scale concentrating solar powered desalination systems:

- Some 900 $Mm^3$ of natural gas could be exported instead of being used for desalination, thus providing hard currency for the country.
- Due to energy storage and hybrid operation with (bio)fuel, concentrating solar power plants can provide around-the-clock firm capacity that is suitable for large-scale desalination either by thermal or membrane processes.
- CSP-desalination plants can be realized in very large units up to several 100,000 $m^3$/day.
- Huge solar energy potentials of Oman can easily produce the energy necessary to avoid the threatening freshwater deficit currently estimated at 378 $Mm^3$ [8].
- Improved irrigation efficiency, groundwater abstraction control and increased recovery of natural resources through recharge dams are the major actions the Omani government is willing to implement to solve the problem of groundwater deficit by 2020.
- During 2008 the desalinated water was estimated at 138 $Mm^3$/year, 93.4% is produced in the coastal area of Muscat and Barka. It is expected that the demand will reach 221 $Mm^3$/year in 2013, which is an average growth of 12% per year.
- The growth in desalinated water demand is driven by a high population growth as well as the economic growth mainly in the industrial and service sectors. The necessary investment package in the urban water sector is estimated at US$ 1/2 billion for the period 2006–2010 alone without including the Duqum area [9].
- Given the very limited groundwater resources, the future demand of urban water in Duqum should come from seawater desalination.
- It is expected that within one decade, energy from solar thermal power plants will become the least cost option for electricity (below 0.05US$/kWh) and desalted water (below 0.5 US$/$m^3$).
- Advanced solar powered desalination with horizontal drain seabed-intake and nanofiltration will avoid most environmental impacts from desalination occurring today.
- With support from several foreign countries Oman should immediately start to establish favorable political and legal frame conditions for the market introduction of concentrating solar power technology for electricity and seawater desalination.

It is believed that CSP water desalination will provide a sustainable solution to the threatening water crisis in Oman and the region, and will achieve a balanced, affordable and secure water supply structure for the next generation, which has been overlooked by most contemporary strategic analysis.

## 8. Socio-economic impacts

The perspectives of cost reduction of CSP-desalination under the condition that market expansion would take place as described before. The cost of heat from concentrating solar collector fields is at present equivalent to heat from fuel oil at 50 US$/barrel, heading for 35 US$/barrel around 2010 and 20 US$/barrel by 2020 [1]. In the long-term a cost of 15 US$/barrel will be achievable for solar "fuel" while fossil–fuel is not expected to ever return to such low levels equivalent to those in the mid 1990s. This means that heat from concentrating solar collector fields will become one of the least cost options for energy in Oman, if not the cheapest at all. CSP plants providing power and desalted water can be operated economically with attractive interest rates if reasonable, unsubsidized prices are paid either for electricity or water. This must be seen in the context of present power and water utilities in Oman, that often show a zero or negative rate of return of investment, thus highly subsidizing power and water.

While it is clear that the threatening water crisis cannot be solved by conventional desalination, it can indeed be solved by solar powered desalination combined with efficient use of water reserves and re-use of wastewater. Building water supply on limited, fossil energy resources with unknown cost perspectives would be very risky, while building a reasonable share of water supply on renewable resources that become cheaper with time would be rather reasonable.

CSP-desalination can also help reduce the subsidiary load of the government from the power and water sectors and thus liberate public funds that are badly needed for innovation and development.

After comparing the expected cost of solar powered seawater desalination, the cost of measures to increase the efficiency of water use and economic losses induced by the over-use of groundwater, it is clear that the unsustainable use of groundwater is not only a threat

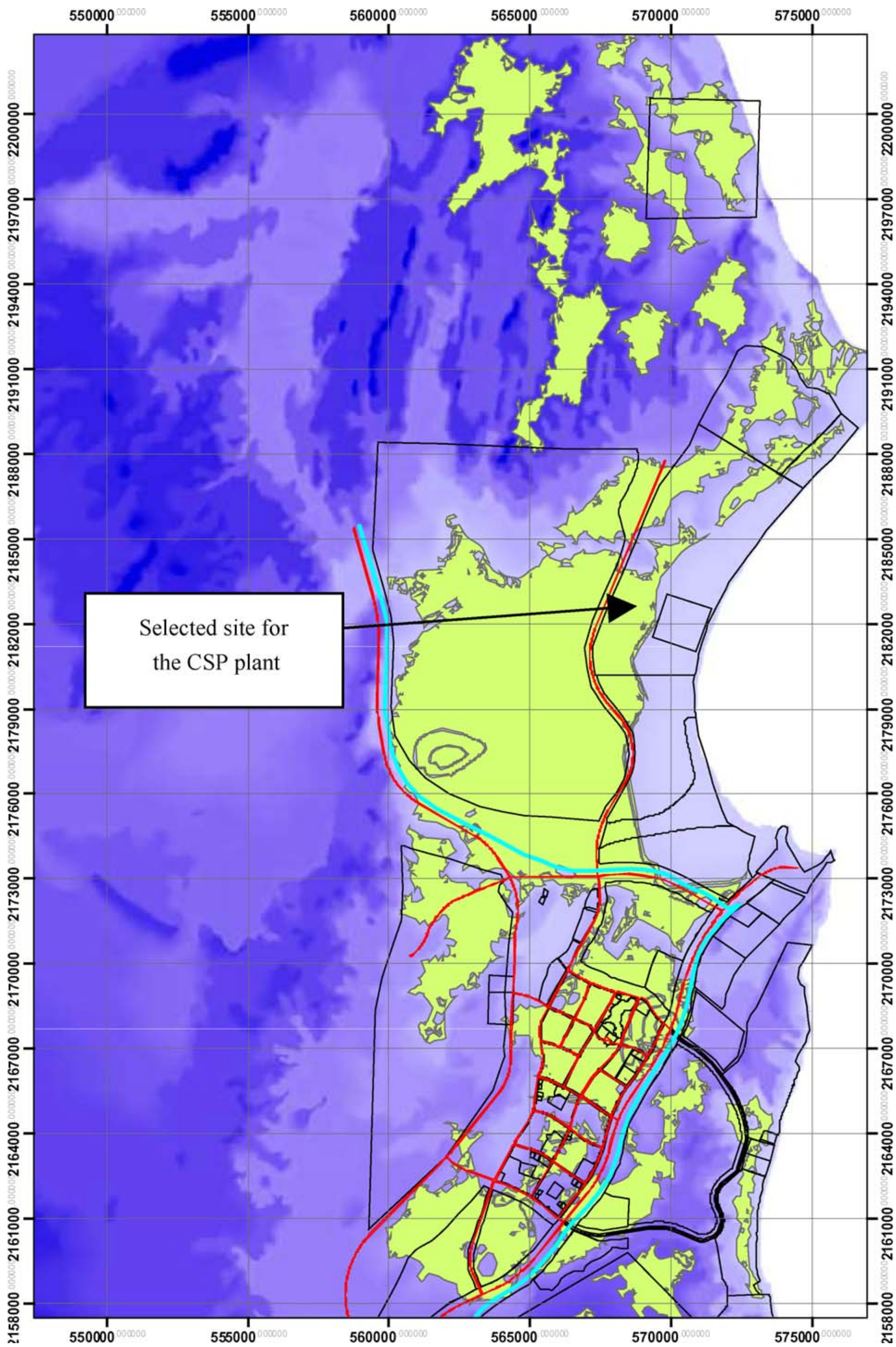


**Fig. 5.** Solar radiation map for Duqum region after filtering slopes higher than 1% and keeping only slopes below 1% (green or light color). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

to the environment, but also to the national economies that suffer under such schemes, with losses of national income by a reduced gross domestic product amounting to billions every year.

The concept of sustainable supply of water for Oman based on efficiency and renewable energy is not only more secure and more compatible with society and the environment, but in the medium-term also cheaper than a business-as-usual approach, that would finally end in a devastating situation for the whole region.

Sound investments and favorable economic frame conditions are now required to start market introduction and massive expansion of CSP for power and desalination. For instance, a population doubling until 2050 in Duqum will certainly only require much more energy and water.

## 9. Environmental impacts

The environmental impacts caused by solar powered seawater desalination. The main impacts from seawater desalination are the following [1]:

- Seawater intake for desalination and for the cooling system may cause impingement and entrainment of organisms.

- Airborne emissions of pollutants and carbon dioxide are caused by the generation of electricity and heat required to power the desalination plants.
- Chemical additives and biocides used to avoid fouling, foaming, corrosion and scaling of the desalination plants may finally appear in the brine.
- Discharge of hot brine with high salt concentration to the sea may affect local species.

In [1], the emissions from power generation have been assessed on a life-cycle basis, including the construction, operation and de-commissioning of the reference CSP/RO and CSP/MED plants, and their impacts have been compared to conventional desalination schemes. The analysis shows that impacts from operation of conventional desalination plants can be reduced by almost 99% using solar energy as they are primarily caused by fuel consumption. The remaining impacts caused by the construction of plants that are dominating in the case of solar desalination are reduced effectively in the course of time due to the long-term change of the Omani electricity mix to a higher share of renewable energy.

Due to the direct impacts of desalination plants to their coastal environment a thorough impact analysis must be performed in every case prior to the erection of large-scale desalination plants, as sensitive species may be heavily affected. Only sites should be chosen that allow for an effective and quick dilution of brine in order to avoid local overheating and high concentration of salt.

Horizontal drain tubes beneath the seabed were recently proposed for intake and discharge, allowing on one hand for a pre-filtering of feed-water and on the other hand for an effective pre-cooling and distribution of the brine. Pre-filtering can be enhanced further by applying nanofiltration, which will require more (solar) energy but will avoid chemical additives like antifouling, anti-foaming and anti-scaling agents as well as biocides. Substituting chemicals by solar energy can thus mitigate both chemical additives and emissions from energy supply.

Advanced future CSP/RO and CSP/MED desalination plants will have the potential to operate with extremely low environmental impacts compared to today's conventional desalination systems.

## 10. Conclusion

Seawater desalination will have a major share on freshwater supply that will be affordable for Duqum in particular and Oman in general and will be based on a domestic energy source and will not cause major environmental impacts, if concentrating solar power (CSP) is used for energy supply. It was found that the amount of solar radiation in the Duqum region is very promising and if CSP is used it will help providing sufficient amount of both electricity and desalinated water. Based on GIS solar radiation calculation, geographical topology, and the master development plan of the Duqum region, the most appropriate site for the CSP plant is selected proximity to the coast in an industrial area.

Absolutely clean desalination plants will be imperative for a massive implementation to solve the alarming water crisis. This can only be achieved if chemical additives can be substituted by enhanced intake and filtering of seawater that will require more energy than usual. Concentrating solar power is the key to this solution, as it is the only source that is at the same time emission free, domestic, large enough to cope with the huge demand, based on available technology and expandable to the necessary large volumes within a time-frame of only 15–25 years.

Together with appropriate measures to increase the efficiency of water distribution and end-use, market introduction of CSP for power and seawater desalination must start immediately, and adequate political and economic frameworks must be established in Oman to foster implementation of first pilot plant in Duqum and to assure a quick expansion of this technology in the whole country and the region. Any delay will increase the danger of a catastrophic depletion of groundwater resources that would have major detrimental effects on economic development and social peace.

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